Mechanistic Investigation of Small-Scale Air-Sea Coupled Dynamics Using LES

Dick K.P. Yue
Center for Ocean Engineering
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139
phone: (617) 253-6823 fax: (617) 258-9389 email: yue@mit.edu

Award Number: N00014-01-1-0159
http://mit.edu/vfrl/www/

LONG-TERM GOAL

Our long-term objective is to obtain a more thorough understanding of the dynamics of coupled boundary layers air-sea transfer (CBLAST) at relatively small spatial scales, by performing direct numerical simulation (DNS) and large-eddy simulation (LES) together with large-wave simulation (LWS) for both air and ocean turbulent flows with surface waves. The primary focus and an ultimate goal is to obtain the physical foundation for the characterization and parameterization of the momentum, mass and heat transfer within the atmosphere-ocean wave boundary layer (WBL).

OBJECTIVES

The scientific and technical objectives of this project are to:

- Develop high-performance DNS and LES/LWS capabilities for coupled air-water wave boundary layers, with a focus on air and water turbulent motions and scalar transport under the influence of coupled free-surface boundary conditions.

- Fully resolve and capture the coupled air-sea-wave dynamics at ocean wave scales. Elucidate the statistics, structures and dynamics of air and water turbulent flows in the vicinity of the air-sea interface.

- Identify and assess the key transport processes within the atmosphere-ocean WBL.

- Assess, develop and validate specialized physics-based turbulence modeling for the atmosphere-ocean WBL.

- Perform direct quantitative comparison and cross-validation of simulations with experimental/field measurements; complement and collaborate with other modeling efforts.

- Establish a physical basis for the characterization and parameterization of the mass, momentum and energy transfer within WBL.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2005**	2. REPORT TYPE	3. DATES COVERED **00-00-2005 to 00-00-2005**

4. TITLE AND SUBTITLE **Mechanistic Investigation of Small-Scale Air-Sea Coupled Dynamics Using LES**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Massachusetts Institute of Technology,Department of Mechanical Engineering,Center for Ocean Engineering,Cambridge,MA,02139**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
Our long-term objective is to obtain a more thorough understanding of the dynamics of coupled boundary layers air-sea transfer (CBLAST) at relatively small spatial scales, by performing direct numerical simulation (DNS) and large-eddy simulation (LES) together with large-wave simulation (LWS) for both air and ocean turbulent flows with surface waves. The primary focus and an ultimate goal is to obtain the physical foundation for the characterization and parameterization of the momentum, mass and heat transfer within the atmosphere-ocean wave boundary layer (WBL).

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

APPROACH

For the DNS and LES/LWS of coupled air and ocean turbulent flows, we have developed a suite of high-performance, complementary computational methods. These include: (i) a boundary interface tracking method (BITM) for low wind speeds (<5 m/s); and (ii) an Eulerian interface capturing method (EICM) for moderate to high wind speeds (>5 m/s), where the waves steepen/break. The numerical schemes of BITM are based on boundary-fitted grids and coupled free-surface boundary conditions. The EICM is based on a level set approach. These developments are at the cutting edge of computational free-surface hydrodynamics. Transport of passive scalars in the coupled air-water flow system is implemented. Both the BITM and EICM codes are optimized on parallel computing platforms to provide high-resolution results in a timely manner.

The BITM method solves the incompressible Navier-Stokes equations for both air and water. Free-surface coupled boundary conditions are used at the air-water interface, with the kinematic boundary condition requiring that the interface remains a material surface, and the dynamic boundary condition specifying a stress balance across the interface. The transport of scalars is governed by a convection-diffusion equation. The governing equations are discretized using a pseudo-spectral method in the horizontal directions and a finite-difference scheme in the vertical direction. A second-order fractional-step scheme is used for the time integration of the flow field evolution, the transport of scalars, and the motion of the air-water interface.

In EICM, the air and water together are treated as a system with varying density, viscosity and diffusivity. A continuous scalar (the level set function), which represents the signed distance from the interface, is used to identify each fluid. The fluid motions are governed by the Navier-Stokes equations while the scalar is advected with the flow governed by a Lagrangian-invariant transport equation. A large wave simulation technique is used to model the effects of small surface wave fluctuations on large waves. The governing equations are discretized on an Eulerian grid using a finite-difference scheme.

WORK COMPLETED

During the fiscal year of 2005, significant progresses have been made in areas of:

(1) *Numerical capabilities*
Major developments include: further development of highly-accurate DNS for air-water-wave turbulent flows; development of LES and LWS to extend the parameter space of simulations; optimization of codes for high-performance computing (HPC) parallel platforms; and obtaining of extensive database through systematic large simulations.

(2) *Physics of air-sea wave coupling*
Key results include: variation of mean velocity and turbulence intensity near the interface; streaky structures in the air and water near the interface and their quantification; illustration of three-dimensional instantaneous turbulence coherent structures; evolution of turbulence coherent vortex structures near the interface; water motion induced micro low-level jets on the air side; transport of passive scalars in the vicinity of the interface; correlation between scalar concentration fluctuations and fluid motions; variation of turbulence macro and micro length scales near the interface; probability

density distribution of fluid motions and scalar concentrations; velocity and scalar spectra and co-spectra; and kinematics and dynamics of steep and breaking waves.

(3) *Modeling of coupled air-water dynamics*
Major results include: turbulence kinetic energy budget near the interface; enstrophy balance; budget of scalar concentration fluctuations; elucidation of turbulence coherent structures using conditional-averaging techniques; quantification of contribution of coherent vortical structures to near-interface scalar transport process; assessment and development of turbulence modeling for air-water coupled turbulent flows; and development of physics-based energy dissipation modeling for breaking waves.

RESULTS

In the fiscal year of 2005 we have obtained substantial understanding of the dynamics of air-water-wave interactions at small scales, based on extensive simulations and thorough analysis. Such understanding establishes a physical basis for the modeling and parameterization of WBL processes.

Through a systematic investigation of the coupled air-water turbulent flow in a canonical Couette flow (Figure 1), we have attained a thorough understanding of the statistical, structural and dynamical features of air-water interactions. In particular, we have studied the near-surface variations of velocity statistics. Figure 2 plots mean velocity profiles for the air and water. The mean shear in the flow is clearly shown. Because the dynamic viscosity of water is significantly larger than that of air, the velocity difference in the water is much smaller than that in the air. The middle figure in Figure 2 shows an enlarged velocity profile in water. It appears that the velocity variation near the air-water interface is similar to that near the solid (top and bottom) wall. To further investigate the near-interface behavior, the right figure in Figure 2 compares the velocity profiles in the local coordinates normalized by wall units. The law of the wall is satisfied for both the air and water motions near the interface. For the air, the near-interface variation appears to be very close to the one typical for a solid wall. For the water, the viscous sublayer is thinner, and the value for the constant B in the log law $u^+ = \frac{1}{k} \ln z^+ + B$ needs to be reduced from 5.0 to 3.0. This difference can be explained by the different restriction mechanisms of the interface on turbulence fluctuations. As shown in Figure 3, on the airside all the three velocity components diminish at the interface, while on the waterside only the vertical velocity is reduced towards the interface. As a result, the water at the interface has more freedom in horizontal movement, and the region over which the turbulence transport is dominated by viscous diffusion is thinner in water.

From our previous study, it is found that turbulent flows near the interface are characterized by coherent structures including splats and anti-splats, hairpin vortices, quasi-streamwise vortices, and interface-connected vortices. After the identification of these instantaneous structures, characterizing and quantifying their effects on near interface transport processes becomes a great challenge. In this study, we employ a variable-interval space-averaging (VISA) technique, which is based on the variable-interval time-averaging (VITA) method developed in experiment. For each type of structures, $O(10^3)$ events are captured with our extensive datasets of simulations. After local conditional averaging, a much smoothed flow field is obtained and contributions of these flow structures to the TKE budget and scalar transport are elucidated. A typical example for the hairpin vortices is shown in the right figure of Figure 1. From the VISA data, it is found that hairpin vortices play a significant role in the air-water interaction and the near-surface transport. Figure 4 shows the vortex-induced motions and scalar fluctuations on a vertical cross-section of the hairpin. It is shown that the head portion of

the hairpin causes a large shear at the interface, which further induces a strong shear flow on the airside. Because of the vertical motions associated with the vortex which is approaching the interface, convection of passive scalars is present. As shown in the right figure of Figure 4, such convection greatly changes the scalar concentration. Of particular importance, the thickness of the scalar boundary layer is reduced significantly and thus the scalar interfacial flux is enhanced.

One important discovery from our study is the airside micro low-level jets which are induced by the water motions underneath. A typical example is shown in the VISA results of splat motions in Figure 5. As water is convected towards the interface during a splat, diverging flow is induced at the interface. Because of the continuity of velocity at the interface, diverging flow must also present on the airside. Because the shear stress across the interface needs to be balanced and because the value of dynamic viscosity of air is substantially smaller than that of water, velocity gradient on the airside is much larger than that on the waterside. As a result, on the airside a jet flow in the vicinity of the interface is present, as shown in Figure 5. Such mechanism is also present in the case of quasi-streamwise vortices. Figure 6 shows the VISA results on a vertical cross-section of the quasi-streamwise vortex. The left figure shows that micro low-level jet is a salient feature in the region to the upper-left of the vortex. Also in that region the convection induced by the vortex makes the thickness of the scalar boundary layer much thinner, as shown in the right figure of Figure 6. As a result, the transfer of the scalar across the interface is greatly enhanced. It is our conjecture that turbulence kinetic energy budget and enstrophy balance is also affected by the presence of micro low-level jets, which is a subject of our on-going investigation.

IMPACT/APPLICATION

This study aims to obtain a fundamental understanding of the air-sea wave coupling dynamics at small scales at low wind speeds. Our work is intended as a small yet essential part of an overall coordinated effort involving field experimentalists, air-sea modelers, and physical oceanographers to obtain improved physics-based parameterizations for air-sea interactions. Our numerical simulations will provide detailed descriptions of the air-sea-wave boundary layer at small scales, and a physical basis for the modeling and parameterization of transport process within the atmosphere-ocean wave boundary layer. The simulations will also provide the essential tools for the interrogation of sparse experimental datasets and the extension of parameterization to full scale.

TRANSITIONS

The numerical datasets obtained from this project will provide useful information on physical quantities difficult to measure. Simulations in this study will provide guidance, cross-calibrations and validations for the experiments. They also provide a framework and a physical basis for the parameterization of coupled air-ocean-wave dynamics.

RELATED PROJECTS

This project is part of the ONR-sponsored Coupled Boundary Layers Air-Sea Transfer (CBLAST) DRI (http://www.whoi.edu/science/AOPE/dept/CBLASTmain.html). Our numerical study is performed in close collaboration with experimental observations and other modeling efforts.

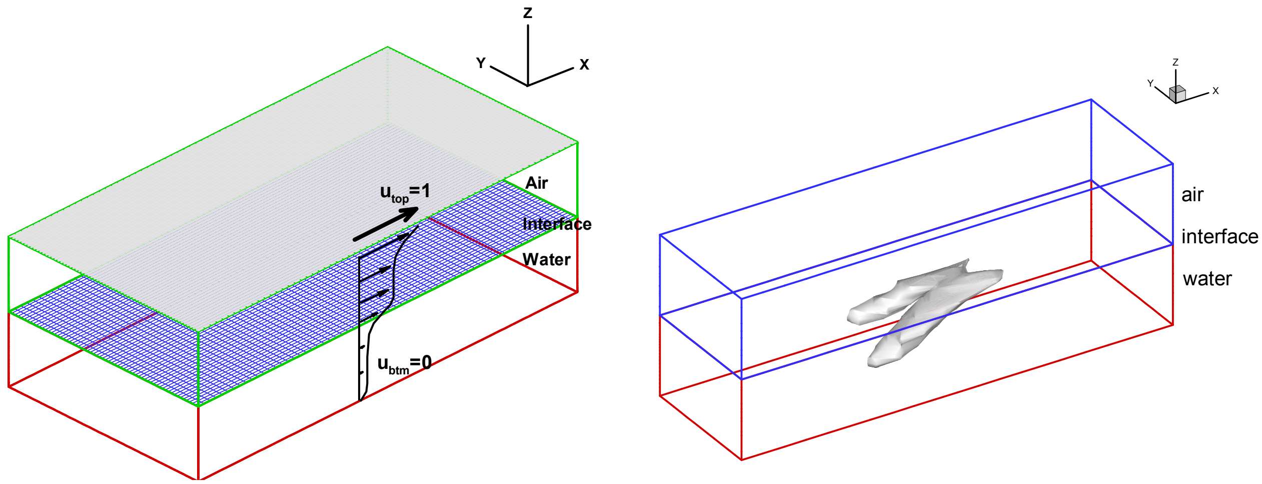

Figure 1. Left: schematics of coupled air-water Couette flow. Right: coherent hairpin-shaped vortex structure near the interface. The vortex structure is indicated by the isosurface of the second largest eigenvalue of the vorticity-strain tensor $S^2 + \Omega^2$. Plotted is the conditionally-averaged result of O(3000) instantaneous hairpin vortices.

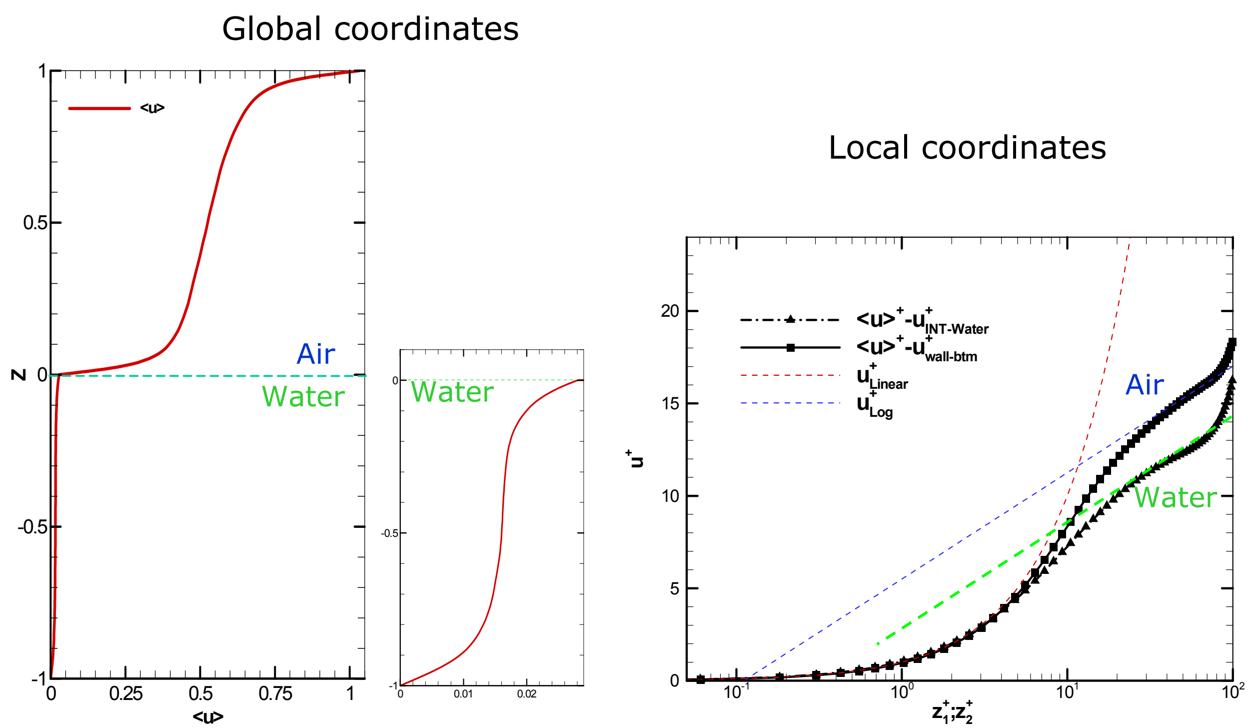

Figure 2. Comparison of air and water mean velocities in the coupled boundary layer.

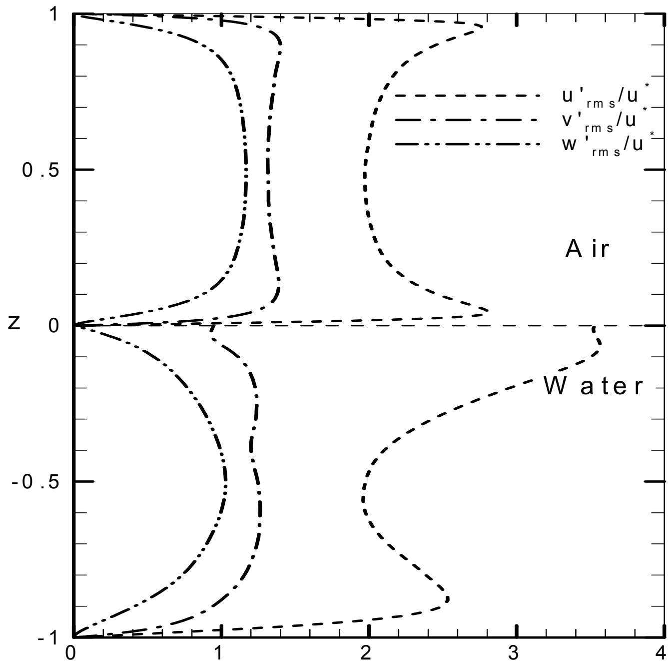

Figure 3. Profiles of velocity fluctuations normalized by shear velocity.

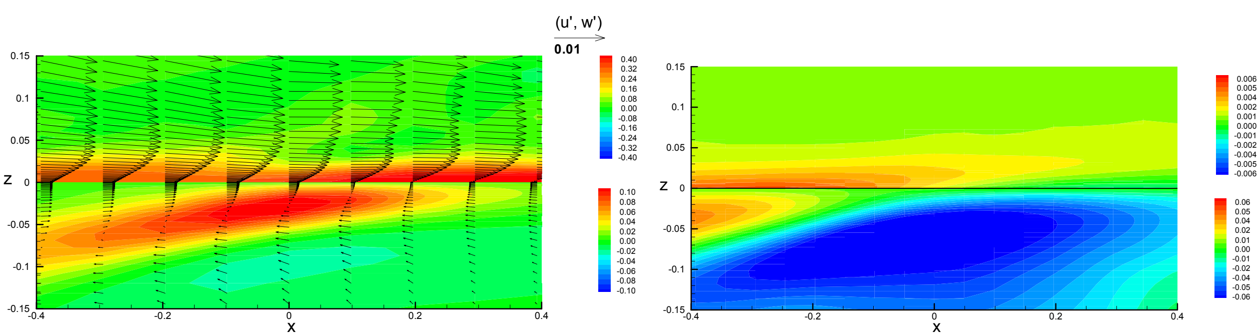

Figure 4. Hairpin vortex on the waterside and the induced shear flow on the airside, and their effects on passive scalar transport near the interface. Shown in the left figure are contours of vorticity component ω_y and fluctuation velocity vectors (u', w') on a vertical $x-z$ cross-section which is located at the center of the hairpin vortex. Shown in the right figure are contours of the scalar concentration fluctuations. Plotted in the figures are conditionally-averaged results based on O(3000) instantaneous quasi-streamwise vortices.

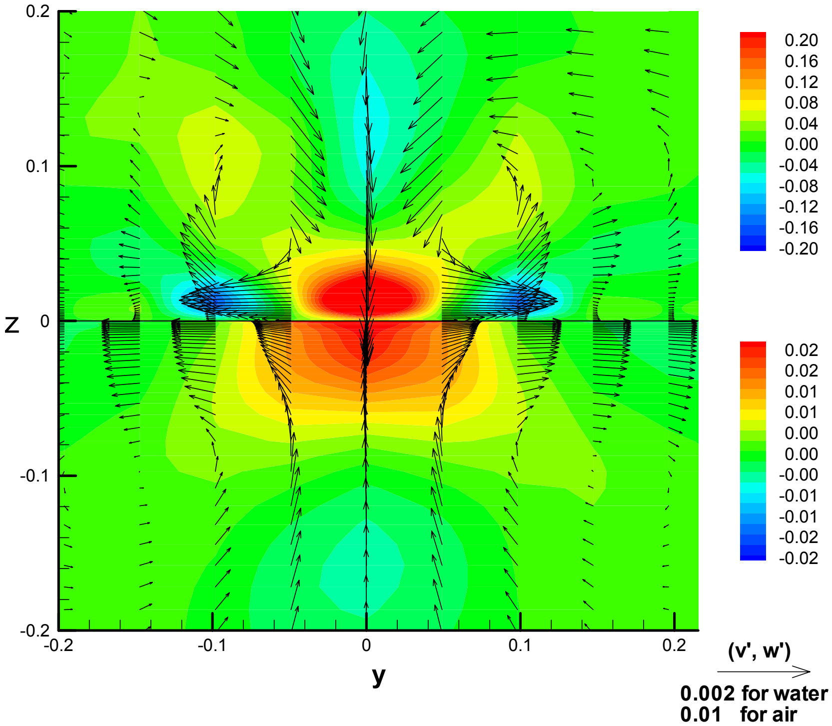

Figure 5. Splat motion on the waterside and the induced micro low-level jet on the airside. Shown in the figure are contours of surface divergence $(\partial u/\partial x + \partial v/\partial y)$ and fluctuation velocity vectors (v', w') on a vertical $y - z$ cross-section which is located at the center of the splat. Plotted in the figures are conditionally-averaged results based on O(3000) instantaneous splat events.

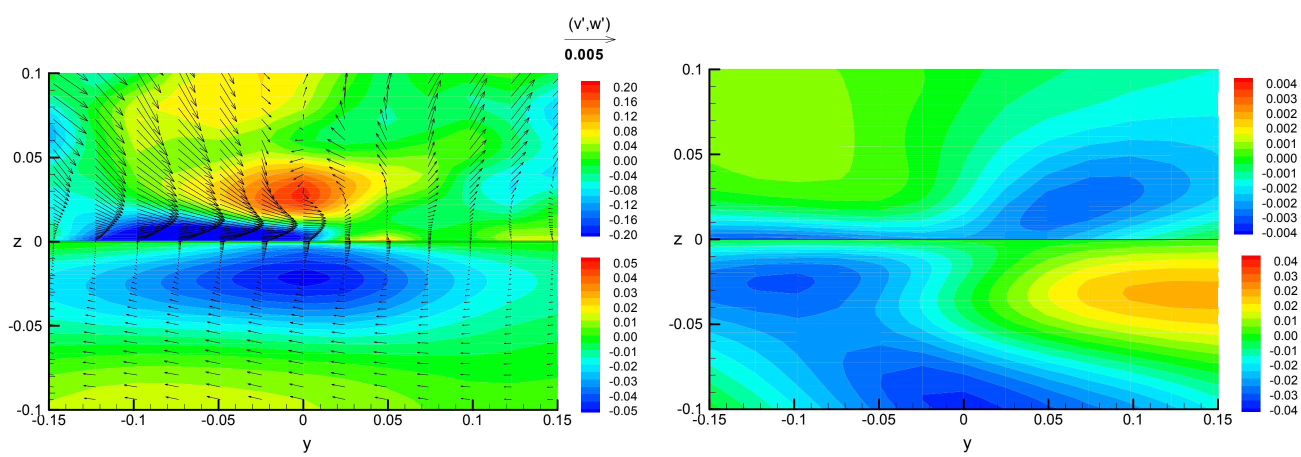

Figure 6. Quansi-streamwise vortex on the waterside and the induced mirror vortex and micro low-level jet on the airside, and their effects on passive scalar transport near the interface. Shown in the left figure are contours of vorticity component ω_x and fluctuation velocity vectors (v', w') on a vertical $y - z$ cross-section which is located at the center of the quasi-streamwise vortex. Shown in the right figure are contours of scalar concentration fluctuations. Plotted in the figures are conditionally-averaged results based on O(3000) instantaneous quasi-streamwise vortices.